Applied Energy 286 (2021) 116513

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The promise and challenges of utility-scale compressed air energy storage in aquifers

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HIGHLIGHTS

- Feasibility overview of compressed air energy storage in aquifers is presented.
- Two energy storage projects are analyzed and experiences are introduced.
- The challenges and suggestions for site selection and air injection are described.

ARTICLE INFO

Keywords:
Compressed air energy storage
Aquifers
Storage efficiency
Pittsfield test
Iowa Stored Energy Plant Agency project

ABSTRACT

Widely distributed aquifers have been proposed as effective storage reservoirs for compressed air energy storage (CAES). This aims to overcome the limitations of geological conditions for conventional utility-scale CAES, which has to date used caverns as the storage reservoirs. As a promising technology, compressed air energy storage in aquifers (CAESA) has received increasing attention as a potential method to deal with the intermittent nature of solar or wind energy sources. This article presents a selective review of theoretical and numerical modeling studies as well as field tests, along with efficiency and economic analyses, to assess the feasibility of the emerging technology. Although some field tests suggest that a large bubble could be created in aquifers to sustain the working cycles at target rates, challenges remain before the technology can be recommended for wide deployment. The geological critical safety factors affecting the gas bubble development and sustainability of operation cycles include the geological structure, aquifer depth, and hydrodynamic and mechanical properties, such as porosity, permeability, compressibility, and mineral composition. Moreover, the injection/withdrawal well configurations and oxidation reactions caused by the oxygen in compressed air should also be considered. The failed attempt of renewable energy combined with CAESA in Iowa is described and the lessons learned are summarized. Combining CAESA with thermal storage, using CO_2 as cushion gas, horizontal wells or hydraulic fracturing, and man-made boundaries are proposed to improve CAESA efficiency but need further study for future applications.

1. Introduction

Renewable energy, such as wind and solar power, has been rapidly acquiring a growing share of the energy market recently due to growing concerns about greenhouse gas emissions, increasing political incentives and declining technology cost [1]. However, these renewable energy sources are intermittent and unstable, usually having balancing issues – wind or solar energy is often more available when the loads are low. As a

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https://doi.org/10.1016/j.apenergy.2021.116513
Received 22 June 2020; Received in revised form 12 January 2021; Accepted 13 January 2021

result, deliberate curtailment of generation (a reduction in the output of a generator from what it could otherwise produce given available resources [2]) becomes ubiquitous in the wind and solar power industry. It was reported that the curtailment rate of renewable energy ranged from 1% to 3% in some countries, such as the United States, Spain, Italy, Ireland and Germany, in 2013 [2], and surprisingly reached 15% in China in 2015 [3].

Utility-scale energy storage provides a solution to the intermittency of renewable energy [4]. So far, there are two options for utility-scale energy storage that have been established commercially. One is pumped hydroelectric energy storage (PHES) and the other is compressed air energy storage (CAES) [5]. A PHES facility can provide a huge energy storage capacity at a low operational and maintenance cost with a round-trip energy efficiency of up to 80% [6], but it needs prohibitively high initial investment for construction and casts huge environmental footprints and ecological impacts because of its land and water resources requirements [7]. In contrast, a CAES facility requires mush less capital to construct and has minimal impact on the land surface and the surrounding inhabitants, and it is much more flexible in regard to storage capacity and installment location [4,6,8]. These features favor CAES as an effective energy storage approach for renewable energy.

A typical CAES system is composed of a compressor, a storage reservoir and a turbine. Three types of reservoirs can be used as the storage reservoir for a utility-scale CAES system. They are salt caverns, depleted gas reservoirs, and aquifers.

Salt caverns are ideal storage reservoirs for CAES due to their safety and stability with low operational cost [9]. Both existing CAES power plants (one in Huntorf, Germany and the other in McIntosh, US) employ salt caverns [10–12]. However, cavern deformation over time potentially threatens the well's integrity [13], the same as in hydrogen cavern storage due to the dynamic pressure–time gradient [14]. Another non-negligible issue is that salt caverns usually occur in areas far from the power plant and/or in areas without demand for the balancing of electricity loads. This may result in high cost for electricity transmission, affecting the system's economic benefits [15]. These issues greatly restrict the application of CAES [16].

As porous media, depleted gas reservoirs and aquifers have much wider distributions than salt caverns and can provide sufficient storage volume for CAES as well. With abundant geological information and numerous wellbores for exploration and gas development, depleted gas reservoirs may be the easiest among the three types of reservoirs to develop, operate and maintain a CAES system. Nonetheless, aquifers may have more potential to combine with renewable energy for a CAES utility because they are more geographically available than gas reservoirs and more flexible in supporting different scales of CAES systems with a wide range of capacities.

Most of the current reviews of CAES discussing system designs, efficiency improvements and coupled-system development are based on using caverns as the storage reservoir [17–20]. Reviews of CAES employing aquifers as the storage reservoir are quite few at the present time. Hence, in this review, we focus on CAES in aquifers (CAESA), in the hope of filling a gap in the literature while in the meantime outlining the full process of developing a CAESA system. In this selective review, we briefly introduce the prototype of CAES and its later improvements, summarize CAESA development history, and analyze the critical factors that affect a CAESA system development from site selection and initial bubble formation to working cycle maintenance. Major challenges encountered in CAESA field tests and projects of integrating CAESA with wind power plants are also discussed. We hope that this review can provide a thought-provoking reference for applying aquifers to utility-scale energy storage to improve the reliability of renewable energy.

1.1. General concept of compressed air energy storage in aquifers

1.1.1. Conventional CAES and later improvements

Before discussing CAESA, we first briefly introduce conventional CAES. A typical CAES system consists of a compressor, a storage cavern/tank and a turbine (Fig. 1). A working cycle of such system involves three stages. The first stage is transforming the off-peak electricity into mechanical energy by compressing air to high pressure, during which heat is generated simultaneously. Then, the compressed air is injected into an underground cavern for storage through a wellbore [21]. The third stage is to recover the energy for the peak load by withdrawing the compressed air and reheating it (typically a small amount of natural gas is needed) in the course of sending it to the turbine for electricity generation [22].

The basic principles, past milestones and recent developments (1975–2015) of CAES have been comprehensively reviewed in detail by Budt et al. [17] and Wang et al. [18]. The two existing CAES plants, one installed in Huntorf, Germany in the 1970 s and the other installed in McIntosh, US in the 1990 s, both use salt caverns as the storage reservoir and have storage capacities of 270 MW and 400 MW, respectively [10–12]. The detailed parameters and operational data about CAES in these plants can be found in Crotogino et al. [10], Hounslow et al. [12] and Budt et al. [17].

The round-trip energy efficiency of a traditional CAES facility is about 50% because the heat generated in the first stage is discarded and additional fuel (natural gas) is needed for the third stage [23]. This is a major drawback of traditional CAES compared to PHES if for no other reason than greenhouse gases are produced during the energy recovery phase by the combustion of natural gas. Thus, studies about CAES mainly focus on energy efficiency improvement. With regard to the components above ground surface, it is suggested that the compressor and the turbine should be matched to reduce unnecessary energy loss [24]. Glendenning et al. [25] proposed that heat generated in the first stage be used for the third stage to reduce the additional fuel consumption. So, a thermal storage container made of refractory materials with high heat capacity and resistance to mechanical degradation and oxidation was added to the system in the McIntosh plant, to store the heat generated in the compression stage for the heating in the later decompression stage. Operational data from the plant showed that the round-trip efficiency increased to 54% [26,27].

New ideas or techniques were proposed later to improve the energy efficiency of CAES, such as adiabatic compressed air energy storage (A-CAES), compressed air energy storage with thermal energy storage (TES-CAES), liquid air energy storage (LAES), isothermal compressed air energy storage (I-CAES), underwater compressed air energy storage (UW-CAES), and supercritical compressed air energy storage (SC-CAES) [23,28,29]. The round-trip efficiency of a unit can approach 68% at nominal load, but it reduces to 52% and 28% at 50% and 10% loads, respectively [30]. An A-CAES system, which uses the heat released during compression to reheat the air in decompression, can achieve a round-trip efficiency of up to 70% [31]. This indicates that a relatively low energy efficiency may not be an issue for CAES anymore.

More recently, advanced adiabatic CAES (AA-CAES), in which no fuel combustion is needed in the third stage, has drawn a great amount of attention from academia and industry [32]. An AA-CAES system stores the compression heat separately through adiabatic compression and reuses the heat for the later expansion stage. The theoretical system efficiency of AA-CAES could be over 60% [33–35]. However, the exhaust temperature from the AA-CAES low-pressure turbine was found to be still too high and this would cause huge energy loss [36]. Thus, packed bed (PCB) heat exchangers were proposed to replace the indirect heat exchangers in an AA-CAES system [37]. Simulations showed that the system efficiency of an AA-CAES system with PCB thermal energy storage can be 70% when the thermal efficiency of the reservoir reaches 95% [23]. So the world's first AA-CAES demonstration plant – ADELE at Saxony-Anhalt in Germany, which is currently under development, aims for a cycle efficiency of 70% [18].

Most recently, CAES has been innovatively proposed to combine with other types of energy systems for better system efficiency and performance. For instance, a hybrid energy storage system with

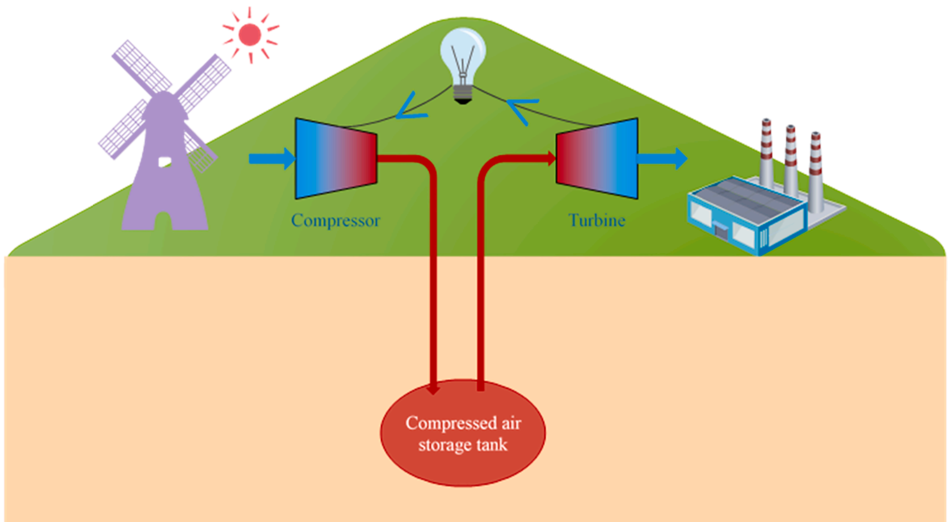

Fig. 1. A schematic diagram of a CAES system (the injection and production processes are achieved through one wellbore).

compressed air and hydrogen storage can realize an efficiency of 38.15%, higher than a system with pure hydrogen storage [38]. A hydro-thermal-wind-solar hybrid power system can be optimized with CAES to have higher voltage security [39]. Incorporating CAES with caverns into a low-temperature thermal energy storage system can be beneficial to the system's performance [40]. If a wind power system is integrated with diabatic CAES, the frequency deviation of the system from the variability of the wind farm power could be substantially reduced [41]. Exergy analyses of the world's first grid-connected underwater compressed air energy storage plant in Toronto, Canada, show that the system exergy destruction ratios under real and unavoidable conditions are 47.1% and 15.9%, respectively, indicating that the plant has great potential for energy efficiency improvements [42]. Reusing natural gas storage sites for CAES can offer a cost-effective alternative for utility-scale energy storage [43,44]. Steel pipe piles can be viable for small-scale CAES [45]. A steady-state input/output model of the trigenerative CAES system has been presented and validated with experimental results [46]. Other storage systems have been proposed, such as compressed carbon dioxide energy in aquifers [44,47–49] and mine golf [50]. Similarly, the first grid-connected underwater CAES system has been implemented in Lake Ontario in 2015 [42,51], indicating that the system is quite flexible and can scale with depth in a marine environment.

1.1.2. CAESA and its development history

A CAESA system consists of the same components as a CAES system and works with the same three-stage cycles. The main difference is that CAESA uses aquifers instead of caverns as the storage reservoir (Fig. 2). Impermeable strata (cap rock) overlying the aquifer are needed to provide a sealing structure for the reservoir. Prior to the system starting working cycles, an air bubble (cushion gas) must be generated in the aquifer first because the aquifer was initially saturated with water. The cushion gas is used to sustain the pressure support for the working air and help prevent water flowing back into the well during air production [1,52].

As shown in Fig. 3, research interest in CAESA has experienced three periods: germination and rapid development (1940 s to 1980 s), stagnation (1980 s to 2000 s) and revived rapid development (2000 s to the present) [17]. The germination period dates back to the early 1940 s, along with the development of fundamental theories to store electrical energy by means of compressed air [17,55]. Until 1960, the CAES/CAESA technology developed slowly due to a lack of demand for grid-connected energy storage. Starting in the 1960 s when nuclear power and coal-fired power plants developed fast, the growing gap between the peak and valley loads in the power systems drove CAESA studies into a rapid development period. In the 1970 s, the so-called energy crisis promoted the development of large-scale energy storage technologies, including CAESA. An intensive research and development program of CAES was carried out in the US to reduce oil consumption, make more effective use of energy generation capacity and rely less on scarce energy sources. However, due to high-cost reasons and rapid expansion of variable load plants, studies on CAESA soon entered a period of slow development until the 2000 s when renewable energy became increasingly important.

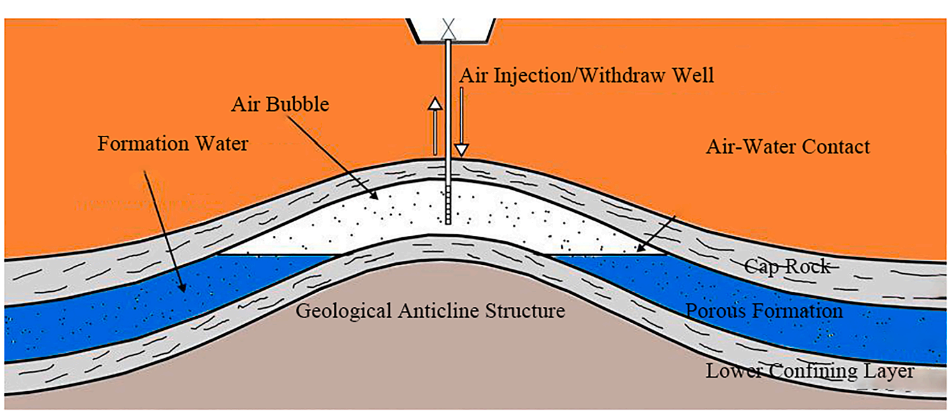

Fig. 2. A schematic diagram of CAESA (modified after Wang [53] and The Hydrodynamic Group [54]).

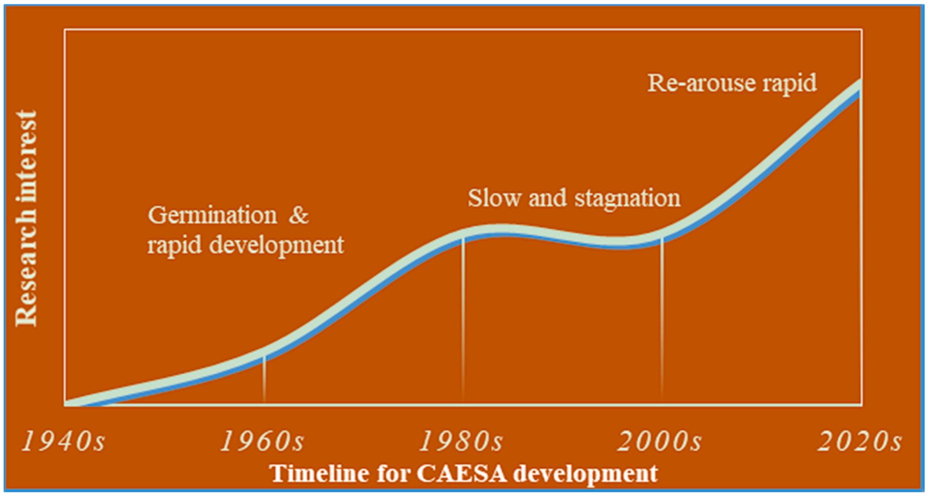

Fig. 3. The general research trend of CAESA development.

Since 2000, many efforts have been made to boost the development of CAESA, aiming to provide a better solution to grid stability and integration in renewable energy generation. Annual publications on CAESA increased rapidly from 1998 to 2020 (Fig. 4), with growing confidence that CAESA is capable of providing a solution to large-scale energy storage with high flexibility and cost-effectiveness.

2. Feasibility, efficiency and economic cost of CAESA

2.1. Theoretical understanding and analogical comparison

Feasibility studies for CAESA need to answer two principal questions: (1) whether there is sufficient pore volume in the aquifer to store the air for operation; and (2) whether the aquifer is capable of sustaining the pressure (2 ~ 8 MPa) during the target working cycles on a daily basis over the entire facility life. The feasibility of CAESA has been studied for more than three decades through analogical, analytical, numerical and experimental methods.

The essence of CAESA described by Oldenburg and Pan [1] is that the enthalpy carried by the injected air is manifested in elevated air pressure and increased liquid and rock temperature. With this conceptualization, the energy stored in aquifers was calculated as follows [1],

$$E_2 - E_1 = C_v \frac{M}{ZR} V_{res}\phi(1-S_r)(P_2 - P_1) + V_{res}(1-\phi)\rho_R C_R (T_2 - T_1) + V_{res}\phi\rho_L C_{VL}(T_2 - T_1) \quad (1)$$

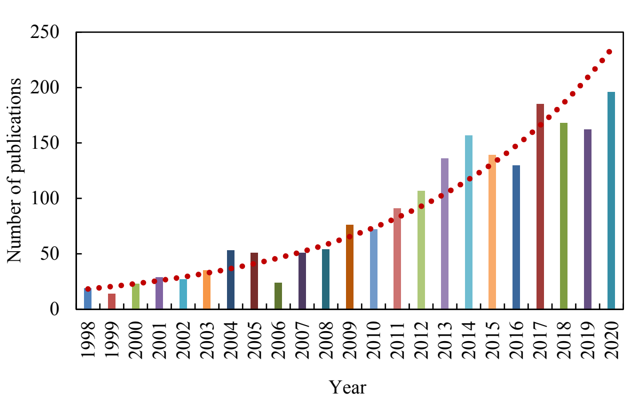

Fig. 4. Number of publications in the last two decades (Keywords: compressed air energy storage and aquifer, Data due: 2020–11-18, Data).
Source: www.sciencedirect.com

where E is Energy (J), 1 and 2 indicate before and after the compressed air injection; C_V is the heat capacity at constant volume (J kg^{-1} K^{-1}); M is mass accumulation term (kg m^{-3}); Z is the gas compressibility factor and R is the gas constant; V_{res} is the reservoir volume (m^3); ϕ is the porosity of rock; $S_r$is the saturation; P is pressure (Pa); $\rho_R$andρ_L are the densities (kg m^{-3}) of rock and liquid phases; C_R is the heat capacity of the rock (J kg^{-1} K^{-1});C_{VL} is the heat capacity at constant volume(J kg^{-1} K^{-1}) of liquid; T is the temperature (°C).

The idea of using aquifers for CAES is similar to natural gas storage. Leading researchers in natural gas storage, such as Katz and Lady [56] have contributed the early development of the theoretical foundations for CAESA. Though most knowledge about natural gas storage is applicable to CAESA, important differences between these two systems must not be overlooked. One is that the CAESA working cycle is on a daily or weekly basis, rather than that of natural gas storage mostly on a seasonal basis. The other is that air is more viscous than natural gas, and the injected air is stored at an elevated temperature.

2.2. Analytical and numerical simulations

A 1D model was developed to investigate the cycling of the flow field caused by heated dry air injection around a single well in an aquifer [57]. This study provided the earliest understanding about the performance of CAESA and became the foundation for later modeling work for CAESA. This study concluded that 1) the permeability and mass flow rate per unit thickness of the aquifer are the most influential parameters; 2) high-temperature air injection will lead to a decrease in deliverability of compressed air during discharge; 3) most of the injected thermal energy concentrates in the area next to the well due to the relatively large volumetric thermal capacity of the reservoir rock; therefore 4) the thermal cycling during charging and discharging can only be observed within a few meters around the well; and 5) the development of reservoir temperature distributions is mostly determined by the flow field (forced convection), but is not significantly affected by variations in the reservoir's physical properties.

With regard to the cushion gas bubble development, it was found that 1) the near-wellbore region can be rapidly dehydrated during the bubble development; 2) outward moving velocity of the dry front (the sharp interface between air and liquid water) increases with injection temperature; 3) net reservoir dehydration rates increase with an increase in injection temperature and decrease in injection humidity; 4) pore plugging is more prone to moist air injection than dry air injection; and 5) the temperature cycling and thermal development are not affected by the presence of residual water [58,59].

An approximate analytical solution was developed by Kushnir et al.

[60] for the pressure variations within the anisotropic reservoir porous space. The results indicate that water coning is a factor that could severely limit the discharge air flow rate and the analytical solution can also be used to construct a solution for multiple well systems. Based on Kushnir et al. [60], a mathematical model of CAESA was established and applied to designing and analyzing a 3 MW system [61].

More sophisticated models have been developed recently to further study the feasibility of CAESA [1,60,62–66]. With a rigorous wellbore-reservoir coupled simulator based on TOUGH2 [67], Oldenburg and Pan [1] studied energy fluxes, storage efficiency, and the effects of native fluids on aquifers for CAESA. They found that energy is stored across a pressure gradient during working-gas cycling in porous media aquifers, unlike in caverns where pressure is essentially spatially uniform, and that a proper-sized reservoir with good caprock and hydrological seals would not lead to excess pressure diffusion. They also suggested that the closure radius of the anticlinal structure containing the aquifer, which is the most favorable structure for CAESA [68], should be large enough to contain the required air volume. Wang and Bauer [53,66] estimated the deliverability and the potential capacity of the reservoir formation for a representative aquifer storage site to operate a large-scale CAESA plant. A 2D radially symmetrical model was developed to estimate the pressure fluctuation inside the storage reservoir during 5 to 10 annual seasonal cycles, using the isothermal two-phase flow (gas–liquid) simulator of the finite element code OpenGeoSys [69,70].

Mechanics is another important aspect that should be considered in the stage of design, operation and monitoring for a CAESA system. TOUGH2-FLAC3D was applied to studying the influence of injection flow rate on the displacement and pore pressure at different locations with injection time [71]. The results indicate that significant displacement of the rock formations would be induced during the formation of initial bubble. Before starting system design, air injection testing is required to obtain data on flow dynamics and rock mechanics [72].

2.3. Field test in Pittsfield

A CAESA field test was carried out under US Department of Energy (DOE) sponsorship in Pittsfield, Illinois in 1981. The field test was to demonstrate the feasibility of air injection/withdrawal and evaluate the system's performance after the idea of small-scale CAESA was suggested in 1979 [73]. The test was the first one of its kind with aims to 1) examine the physical, chemical, and mineralogical effects of CAES on reservoir rock, cap rock and wellbores; 2) compare numerical modeling with field results for bubble development and water displacement, thermal growth and cyclic thermal performance; and 3) evaluate system performance with respect to bubble growth rate, mass transfer rate, thermal development and recovery, water production, and entrainment of mineral particulates. The results from the test demonstrated that a large bubble could be created by injecting air into the aquifer and this bubble was able to sustain the working cycles at target rates.

The field test was conducted in the Pittsfield dome in Pike County, Illinois, from 1981 to 1984 [73–75]. Two second-order closures in a doubly plunging anticline extending about 25 km were considered in the early assessment (Fig. 5-a) [73]. However, only the closure closer to Pittsfield (shown in the red box in Fig. 5-a) was confirmed by subsequent seismic survey and exploratory drilling with a diameter of 300 m and a closure (the vertical height from the top of the anticline down to the point where gas would first leak away around its edge) of 7 to 11 m (Fig. 5-c) [73,74]. The reservoir was highly permeable quartz-dominated St. Peter sandstone with a thickness of 69 m, successively overlain by 10-m thick Joachim dolomite, 34-m thick Platteville dolomite and 42-m thick Galena limestone (Fig. 5-b). The St. Peter/Joachim contact was 197 m below ground surface. Core tests showed that the cap rock formations were sufficiently impervious to hold the compressed air during the lifetime of the field test [73], and that St. Peter sandstone has average gas permeability of 700 mD in both vertical and horizontal directions with an average porosity of 20%, indicating good fluid storage and flow characteristics [54].

The injection/withdrawal well (I/W) was drilled at the highest point

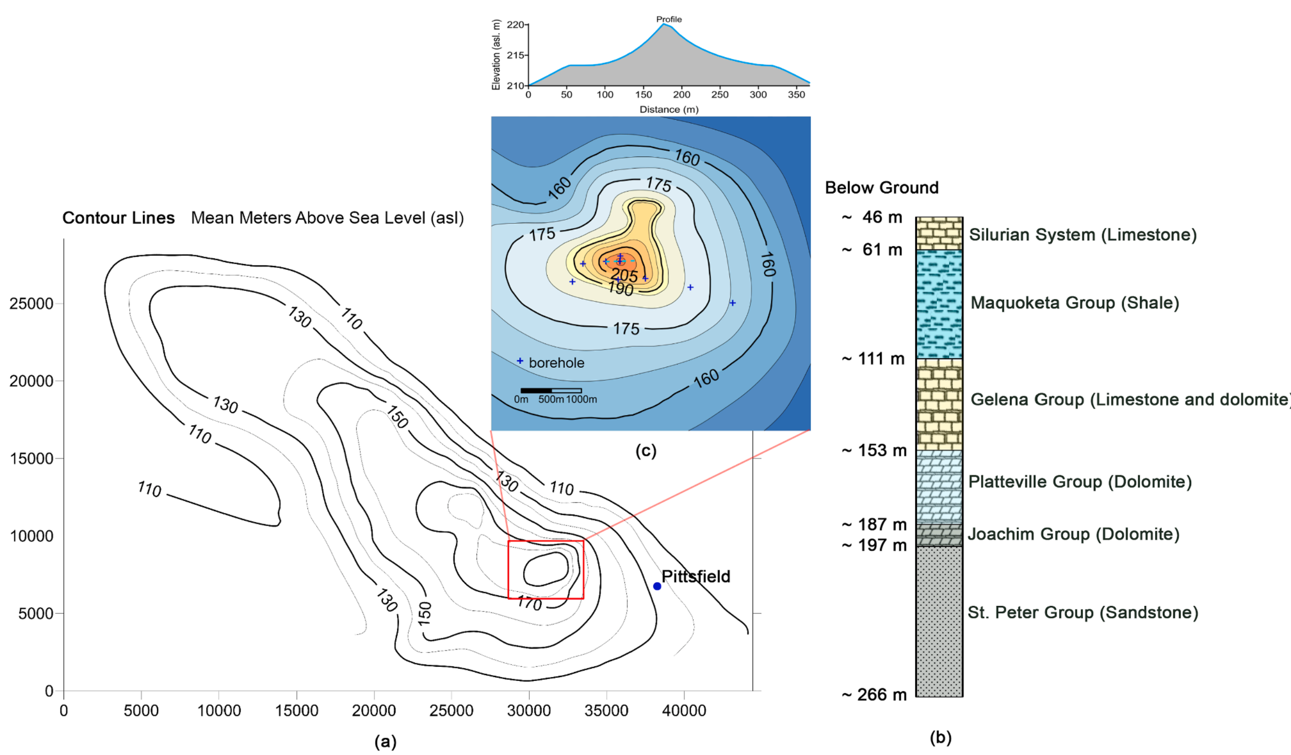

Fig. 5. (a) The structure of the Pittsfield dome indicated by the uppermost Silurian contours; (b) stratigraphy of the Pittsfield dome below the Mississippian System; and (c) the well-defined closure indicated by the contours of the upper Ordovician Maquoketa shale (modified after Allen et al. [73]).

of the structure and cored to 204 m below the ground [76] (Fig. 6-a). Eight monitoring wells with different distances from the I/W were also drilled [77]. Monitoring Well Y-H, about 7.5 m east of I/W, was initially used for gas bubble development. St. Peter sandstone can be divided into three layers according to lithology, grain size and hydraulic characteristics (Fig. 6-b). The uppermost layer (Green) is medium- to coarse-grained, poorly cemented, green and light-gray quartz sandstone, with permeability from 600 to 970 mD and effective porosities from 10 to 23%; the middle layer (White) is medium-grained, well cemented, white quartz sandstone, with permeability from 800 to 900 mD and effective porosities from 9.7 to 20.9%; and the bottom layer (Gray) is medium-grained, medium- to dark-gray quartz sandstone, with permeability higher than the upper two sublayers from 1100 to 1300 mD and more evenly distributed effective porosities from 14.2 to 17.7%. The average initial pressure (discovery pressure) of the reservoir is 1.1445 MPa and the initial temperature is 14 ℃ [74]. The critical gas and water saturations are 0.28 and 0.90, respectively [74].

To develop the gas bubble, nearly 2.1×10^6 m^3 (74 million cubic feet) of dry air (with a relative humidity of nearly zero) was injected into I/W through the perforations into the 2.5 m thick green sublayer from October 1982 to April 1983. The mass flow rate and wellhead pressure are shown in Fig. 7. Well Y-H was completed as a second injection well after the gas bubble development and used to assess the white layer performance.

After the completion of gas bubble development, reservoir performance was analyzed based on the data from 16 different flow cycles during the cyclic operation period from April through October of 1983 [74]. The deliverability of the reservoir was calculated using Eq. (2), based on the assumption that air flow in the reservoir is laminar and obeys Darcy's law:

$$Q = \frac{1.48038 \times 10^5 kh(P_f^2 - P_s^2)}{\mu_g(9T/5 + 491.67)Zln(r_e/r_w - 0.75)} \quad (2)$$

where Q is flow rate at standard pressure and temperature (m^3 s^{-1}); k is the reservoir permeability (m^2); h is formation thickness (m); P_f is shut-in reservoir pressure (Pa); P_s is flowing pressure at the injection well bottom (Pa); μ_g is air viscosity at P_f and T (Pa·s); T is reservoir temperature (℃); Z is gas compressibility factor at P_f and T; r_e is exterior radius of reservoir (boundary of air/water) (m); r_w is wellbore radius (m).

The deliverability of the upper two layers (Green and White in Fig. 6b) was found to be satisfactory for CAES, although the white layer has a higher deliverability than the green one (Fig. 8). Log data showing the water saturations *vs* depth in Well Y-H (Fig. 9) confirmed that most of the injected air was contained within the white layer. It is interesting to note that air saturation increases as shale volume decreases (Fig. 9). Gamma ray-neutron logs obtained in wells I/W, Y-H, Y-A, Y-C, and Y-D were used for estimating the air bubble boundary. Assuming a constant bubble thickness of around 3 m and a residual water saturation of 50%, the air-bubble had a maximum extent of about 760 m away from I/W, following the general shape of the reservoir structure (Fig. 6-a). Fig. 10 shows one of the cycles with operation data of the air flow rate, air pressure and temperature, indicating that the targeted cycling operation of CAES is sustained in the aquifer.

2.4. Cycle efficiency for CAESA and cost-effective economics

Energy efficiency is key to assessing the performance of the CAES system. The common round-trip energy efficiency (η) is defined as the ratio of energy produced (E_{out}) and energy stored in (E_{in}) [1,69]. E_{in} includes the energy consumed by the compressor and the additional natural gas added in the turbine. Advanced energetic analysis was conducted by Liu et al. [78] to obtain better understanding with options for improving the overall efficiency. As for the aquifer, SCT (Sustainable Cycle Times), which means that the total number of daily or weekly cycles of the system can be run continuously without air replenishment, is proposed to describe the aquifer storage efficiency [63]. Because the energy stored is in the form of a pressurized gas phase (air) [1], the pressure dissipation in the aquifer, e.g., by water flowing away from the air bubble, should also be taken into account to evaluate the aquifer's storage performance. In addition, due to the air lost in the cyclic process, the amount of air replenishment for sustainable system running is another way to depict the aquifer's performance. Storage efficiency increases with the gas bubble volume and storage formation permeability, as shown in Guo et al [63]. The potential storage capacity is equivalent to approximately 160% of the UK's electricity consumption for January and February 2017 (77 – 96 TWh), with a round-trip energy efficiency of 54–59% [69]. Yang et al. compared the system efficiency performance of daily, weekly and monthly cycles and the results indicate that the energy recovery efficiency of daily cycle is slightly more competitive than other cycle modes [79].

Apart from the advantages of reducing the location limitations, using aquifers as the storage reservoir has apparent economic benefits. Succar et al. [21] found that the construction cost for building a power plant with CAESA is 2–7 US$/(kW·h) while it is 6–10 US$/(kW·h) with CAES in caverns, and the corresponding incremental storage volume expansion extend cost is 0.11 and 2.0 US$/(kW·h), respectively. For a hybrid system using CO_2 as the working fluid, the optimal value of exergy efficiency and unit product cost are 60.5% and 0.23 $/(kWh) [80]. So, the more flexible and cost-effective CAESA looks more promising when it is combined with a renewable energy utility. In addition, different views on the economic performance of CAES are put forward. For example,

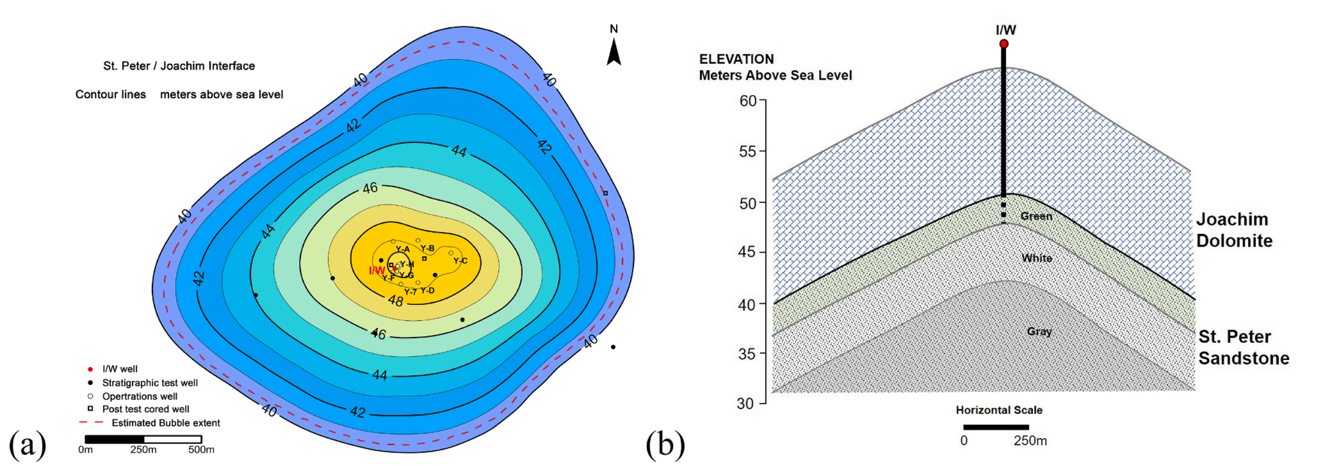

Fig. 6. (a) Contours of St. Peter/Joachim interface elevation and locations of wells; and (b) schematic diagram of the west-east cross-section of the reservoir for the Pittsfield CAESA test (modified after ANR Storage Company [74]).

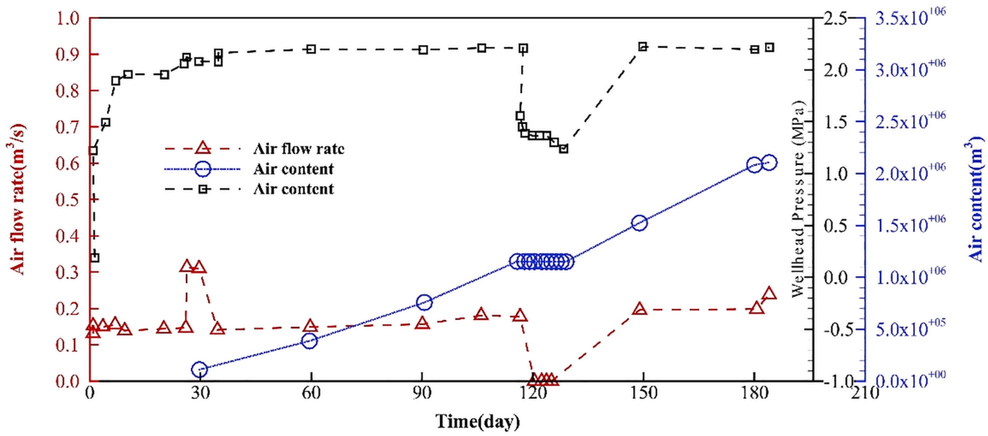

Fig. 7. Mass flow rates and average monitoring pressure during bubble development [74]

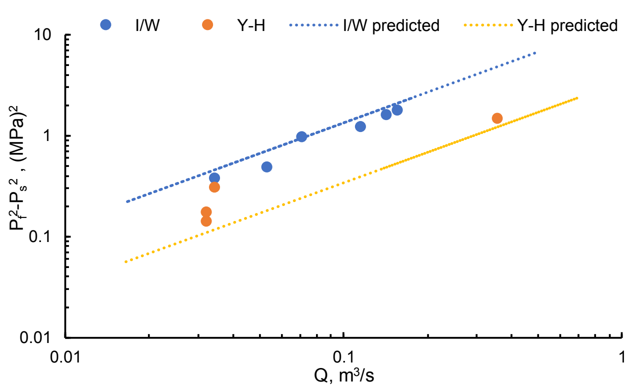

Fig. 8. Deliverability comparison between Wells I/W and Y-H. (Modified after ANR Storage Company [74]).

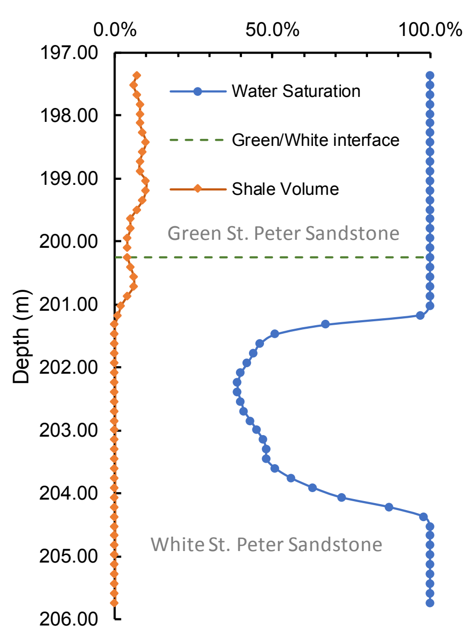

Fig. 9. Water saturation and shale volume along the depth in Well Y-H (plotted with data from ANR Storage Company [74]).

curtailment of variable renewable generation (VRG) may not only lead to avoided investment costs in energy infrastructure but also to avoided operational costs for systems reserve procurement and regulating energy [81]. Based on the data in 2008, a base load wind/CAES system is less profitable than a natural gas combined cycle (NGCC) plant at carbon prices less than \$56/tCO_2 (\$15/MMBTU gas) [82].

2.5. Technical feasibility verified by using depleted gas reservoir in King Island

In 2009, a 300-MW-by-10-hour CAES project was proposed by Pacific Gas & Electric Company (PG&E) to investigate promising technologies that could provide operational flexibility for integrating intermittent renewable resources and balancing supply and demand [72].

Firstly, possible underground storage reservoirs in California, US were examined by considering geological factors such as reservoir size, permeability, porosity, depth/pressure, reservoir thickness, remaining reserves, and trapping mechanism. Two candidate sites in California, King Island and East Island, were left after the screening process.

More detailed information on reservoir rock properties, caprock properties, reservoir pressure, and reservoir fluid was obtained through core drillings. The data indicated that the depleted natural gas reservoir at the King Island site was favorable and more viable. Approximately 500 million standard cubic feet (MMscf) of air was injected into the depleted gas reservoir to develop the initial bubble and obtain important data regarding the reservoir responses to air injection, in terms of flow dynamics, rock mechanics, and the percentage of native gas in the withdrawal stream. Several injection and withdrawal cycles were conducted to test the feasibility of a fully developed CAES system, and results indicate that the reservoir was capable of accommodating the flow rates and pressures necessary for the operation of the facility. The related environmental issues, such as land-use zoning, proximity to sensitive areas, and local community issues, were also analyzed.

The project was ended due to economical uncompetitiveness with alternative storage technologies. Concerns by potential operators included incomplete data regarding the reservoir's characteristics and uncertainty in performance and potential for the corrosion of equipment, management of methane, and oxygen depletion in the withdrawal air stream over time.

3. Challenges, attempts and future development for CAESA

3.1. Challenges for CAESA application in the energy industry

3.1.1. Modeling

The methods for multi-phase flow calculation, especially for air under high pressure and temperature, need updating with new understandings obtained from laboratory experiments, simulations, and field operations. Although we have acquired a practical understanding

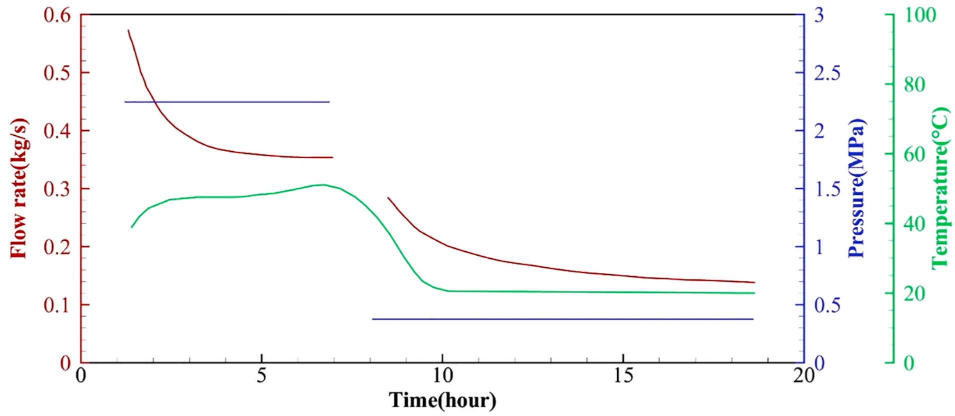

Fig. 10. One of the cycles with operating data of air flow rate, air pressure and temperature [74]

of CAESA, most of this knowledge is inferred from process-similar but working-cycle-different operations such as natural gas storage. For example, the compressed air properties in most of the related numerical simulation studies [1,62,64,67,83] are considered and calculated by the ideal gas law, which would have non-negligible influence under high-pressure conditions. An exception was a study that utilized the Peng-Robinson equation of state for CO_2 aimed at evaluating whether CO_2 could be exploited as an effective cushion gas for CAESA [84]. Studies considering chemical reactions, which might affect CAESA, are not found in the published literature so far.

3.1.2. *Site selection*

Several factors must be considered when evaluating aquifers used for storage reservoirs because several parameters can limit the operation of CAES [85]. Therefore, a precise field study is required to detect favorable areas for subsurface storage of fluids [22]. Allen et al. [73] offer an excellent summary on the related issues. One challenge is the initial air bubble development at the beginning stage, as reported by Moridis et al [86]. The mass of cushion gas is supposed to be 10 to 100 times the cycled mass of air, depending on the energy storage scale [54]. According to Berving and Wallace [87], a minimum volume of around 15×10^6 m^3 of air storage is necessary to generate 150 to 200 MW of electricity over an 8-to-10 h period. Because CAES involves daily or weekly cycles and a great amount of heat is generated during air compression, the aquifer matrix may be adversely affected by frequent pressure and temperature changes, humidity cycles, and the possible oxidation of substances in the aquifer caused by air storage.

According to Allen et al [73], the most favorable reservoir is a doubly plunging anticlinal or dome-like sandstone aquifer with a 200- to −1500 m depth and a minimum thickness and closure of 10 m each, immediately overlain by at least 6-m thick impervious caprock (like shale, dolomite or limestone). Other types of structural or stratigraphic trap, like lenticular porous carbonate reef structures or sandstone lens entirely confined within aquitards or aquicludes, may also be suitable for CAES. The aquifer should be clean quartz sand with interconnected pores to provide paths for air flow [88].

The permeability and porosity of the aquifer should not be lower than 3.0×10^{-13} m^2 (300 mD, 10^{-15} m^2 = 1 mD) and 10% [89], respectively. Although the formation permeability at the gas bubble boundary does not apparently affect the daily cycle efficiency, it will determine the total number of sustainable cycles for the whole life of CAESA [63]. The benefits in terms of exergy are more obvious when the permeability increases from low ($\leq 0.05 \times 10^{-12}$ m^2 or 50 mD) to medium–high values ($\geq 0.25 \times 10^{-12}$ m^2 or 250 mD) [90]. Preferable aquifer ranking criteria based on numerous CAESA projects sponsored by DOE are summarized in Table 1 [21,91]. Guo et al [62] found that the performance of CAES in aquifers could match that in caverns if the reservoir has appropriate properties to develop a gas bubble composed of air. Nevertheless, a wider pressure variation and a more stable temperature change in CAESA were observed. Guo et al. [92] suggested that, for a 200-system-cycles energy storage plant with a 3-hour continuous air pumping rate of 8 kg/s on a daily basis (3 MW energy storage), the optimum range of permeability for a 250-m thick storage formation with a radius of 2 km is 150–220 mD. This range may vary depending on the energy storage objective and aquifer size. Systematic research on the optimum permeability ranges for different energy storage scales is still needed.

3.1.3. *Well configuration*

Well configuration can also affect the performance of a reservoir. Li et al. [93] investigated the influences of the well screen length on CAESA system performance using an integrated wellbore-reservoir simulator (T2WELL [94]). Results showed that the well screen length can affect the distribution of the initial gas bubble. Multiple wells can be used to improve the deliverability, but the number of wells does not necessarily decrease with the increase in formation permeability [53]. For a power output of 321 MW delivered by a given highly permeable formation, the number of continuous power output hours and maximum power output in the first 30 min showed a linear relationship with the number of wells [66]. Wang and Bauer [66] suggested that using six wells in a 20 m thick storage formation with a permeability of 1000 mD is able to support a 6-hour continuous power output of 321 MW for a power plant.

Water coning, i.e., the intrusion of water into the wellbore or its vicinity, may occur during air withdrawal when water underlies the air storage zone. This would cause undesirable effects such as reduced relative permeability to air or totally blocked air flow [73]. An analysis without considering thermal effects performed by Wiles and McCann [95] pointed out that water coning should be included in the site-specific

Table 1
Ranking criteria for candidate sites of CAESA [76,89,91]

Grade	Unusable	Marginal	Moderate	Good	Excellent
Permeability (mD)	<100	100–200	200–300	300–500	>500
Porosity (%)	<7	7–10	10–13	13–16	>16
Reservoir structural and lithological characteristics	Highly Discontinuous	Moderately vuggy limestone & dolomite	Reefs, highly vuggy limestone & dolomite	Channel sandstone	Blanket sands

CAES evaluation, even if the result indicates that water coning may not be a serious problem because the response of the water to the pressure gradients is slow and the duration of the pressure gradients is relatively short.

Fatigue failure of well casings and cement materials is another issue affecting well configuration. Corrosion and wellbore pressure should be taken into account. The maximum charging pressure is determined by the thickness and densities of the geological formations overlying the reservoir and it is suggested that it should not to exceed 80% of the lithostatic pressure of depth [73]. If an average density of saturated overburden is taken as 2306.6 kg/m^3 [96], the corresponding lithostatic pressure gradient will be 22.63 kPa/m such that the maximum charging pressure should be below 18.1 kPa/m of depth [73]. Twelve incidents involving well casings and/or cement leaks in the salt caverns storage described by Bérest [97] suggest that thorough monitoring (tightness tests) and a correct well design would lessen considerably the probability of a casing leak occurring. Pressure monitoring at the cavern wellhead is necessary; at Mont Belvieu, this monitoring provided a warning 15 days before the blow-out. However, in most cases, a pressure drop was not observed, or it was too late when observed, or it was observed after the blow-out (Hutchinson), when the leak path was already fully developed [97].

3.1.4. Oxygen depletion

Oxygen content was found to be lost from the reservoir during the Pittsfield test (Fig. 11). Oxygen depletion will reduce the combustion

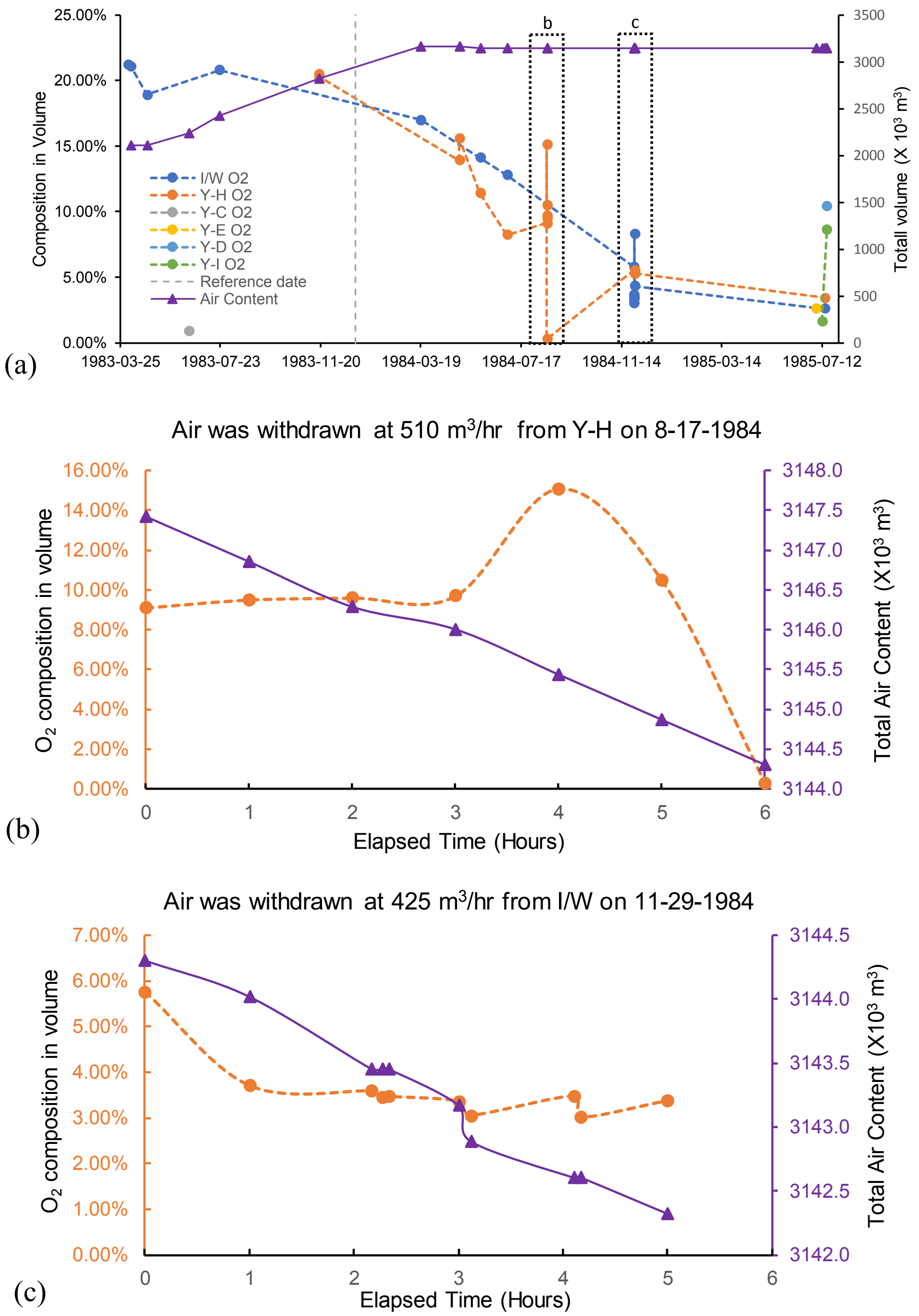

Fig. 11. Changes in oxygen composition (in volume %) in the stored air: (a) air was sampled in different wells over time; (b) when air was withdrawn from Well Y-H; (c) when air was withdrawn from Well I/W (plotted with data from ANR Storage Company [74]).

efficiency if the turbine-based electricity generator needs all of the oxygen content in the air for combustion of natural gas. Oxygen depletion would also impair flow performance. Oxygen monitoring data from the Pittsfield test indicate that the oxygen loss was small when the operation was on a daily basis, but quite significant after the operation was shut-in for a long period or at a place far from the injection-withdrawal wells (Fig. 11). This indicates that oxygen depletion would be serious for an operation based on seasons and thus significantly affect the energy efficiency of CAESA. The most probable reason is oxidation of minerals, particularly iron sulfide, in the reservoir rock matrix [74]. During the daily cycling operation, the oxygen residence time is short, so the oxidation is not significant. Mineralogical analysis of the core samples obtained in the Pittsfield test found that marcasite and pyrite (sulfides of ferrous iron) in the St. Peter sandstone account for the majority of the observed oxygen depletion [74].

In addition, the potential leakage into shallow aquifers would lead to geochemical impacts. Berta presented an integrated experimental and modeling approach examining the site-scale effects of compressed air

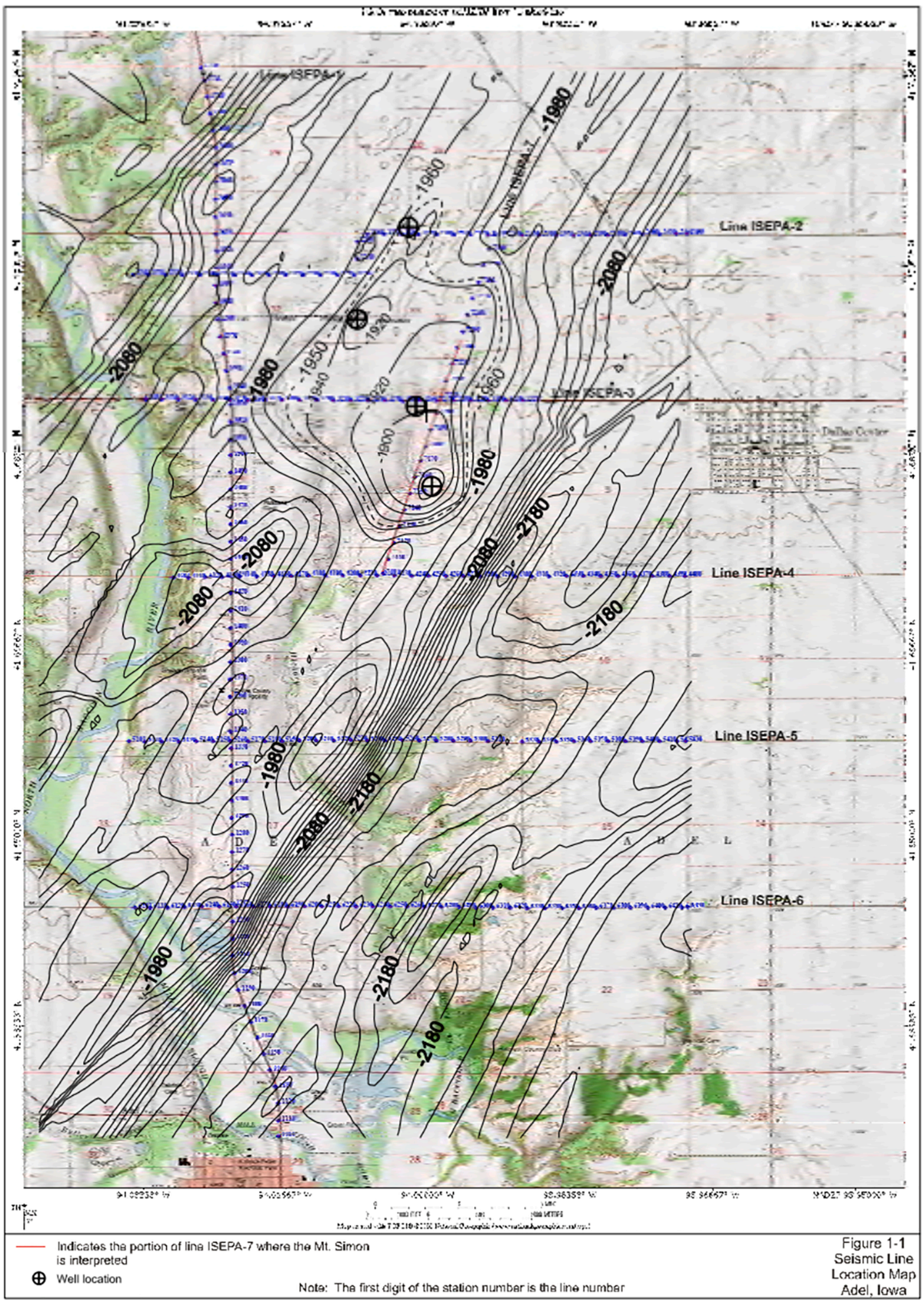

Fig. 12. Sesmic Line Location Map [54]

leakage into a shallow aquifer and the results indicate that pyrite oxidation can be strongly inhibited by surface passivation in carbonate-buffered aquifers [98].

3.2. An attempt to combine with renewable energy

Different scales of hybrid CAES and wind turbine systems have been presented [3]. A case study of a 2 MW hybrid CAES system was conducted by He et al. [99]. The results indicated that the hybrid system were able to effectively stabilize wind power and notably reduce output gaps. CAESA was selected by the Iowa Association of Municipal Utilities (IAMU) to combine the abundant intermittent wind energy in Iowa into the grid. After six years of progressive planning, research, and physical investigations, a geological structure in the Mt. Simon formation in the Dallas Center area (Fig. 12) in the mid-US was taken as the candidate site to carry out the Iowa Stored Energy Plant Agency (ISEPA) CAESA project [100].

Moridis et al. [86] implemented a feasibility study based on the geological data of Redfield (used for natural gas storage for decades) located 6 miles west of the candidate site. The results indicated that the energy storage scale could achieve 135 ~ 270 MW, which means that it is feasible to couple CAESA with a wind energy plant [86]. After this preliminary study, exploration and a series of tests were carried out to describe the Dallas Center Mt. Simon geological structure and determine the reservoir properties (porosity, permeability, compositions and mechanical strength), as shown in Fig. 13. Three new wells were drilled and the subsequent well tests indicated that the proposed candidate site was more challenging than originally expected [54]. The domain turned out to be involve dual dome structures with a closure of<20 m. The Mt. Simon formation at Dallas Center is fine to medium grained silica sandstone with a calcareous cementation. Porosity values of 16% to 17% were consistent with previous analysis, while the permeability values were lower with significant heterogeneity [101]. Furthermore, fluid chemical composition analyses indicated a relatively high concentration of sulfates, showing a higher potential of oxidation of the reservoir.

With updated geological data, a numerical simulation was conducted with TOUGH + H2O/AIR [102]. The results showed that the energy storage scale could be 65 MW by one 1900-m-long horizontal well and 135 MW using 15 vertical wells, with the assumption of a desired air bubble. Furthermore, it was indicated that the development of air-fill process was essential for the whole project. The modeling concluded that an air injection test should be conducted before determining the technical feasibility of the Dallas Center Mt. Simon development for CAESA.

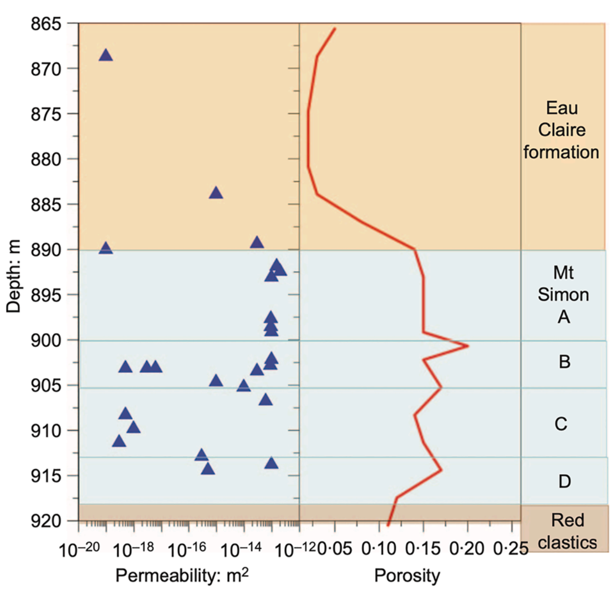

Fig. 13. Distribution of the materials, porosity and permeability at different depths at the Dallas site in Iowa, USA, including the cap rock (Eau Claire dolomite), the aquifer (Mount Simon sandstone) and bedrock (Red-clastics formation) [101] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, the cost estimate and economic studies by Beck [103] indicate that a CAESA project smaller than 270 MW would not be cost-effective [100]. The ISEPA Board was advised that the project at the Dallas Center site should be terminated based on the geology and economic results after 8 years of research and development. Though the project was terminated in July 2011 [104], many lessons regarding site selection, economics and project management were learned, providing valuable information for future projects. For the ISEPA project, the most time-consuming and challenging part was the site selection and geological analysis when there was no existing data or prior use of the reservoir [104].

3.3. Suggestions for future development

With regard to the field operation, more attention should be paid to several aspects. Above all is reliable characterizationing of the reservoir structure. Different geophysical prospecting and drilling exploration methods could be improved or combined together to better understand the geological and hydrogeological characteristics of aquifers. The system's performance largely depends on the aquifer's properties, especially the heterogeneity in porosity and permeability. Cushion gas selection is also important and deserves more studies to control the adverse effects on the reservoir during the storage process [84], like oxygen loss due to mineral oxidation [72]. Based on the previous field test results, many unexpected phenomena arose with heat loss through the wellbore and chemical reactions due to oxidation; thus, integration with other systems [105–107], like thermal energy storage and chemical reaction preventer, also merits consideration and needs further study.

To make a CAESA system more reliable and more effective in energy recovery, it is necessary to reduce the adverse effects on the reservoir during the storage process, such as the oxygen loss due to mineral oxidation [108], heat loss around the wellbore observed in the Pittsfield test, and poor system performance due to low reservoir permeability and movable bubble boundary. Possible solutions to the relevant issues are discussed in detail as follows.

3.3.1. Using CO_2 as cushion gas

CO_2 was proposed as cushion gas (Fig. 14) for CAES in an international patent in 2009 [109]. Due to CO_2 having a greater effective gas compressibility than air, this invention may not only increase the efficiency of gas storage operations but also offer a new option for carbon sequestration to reduce greenhouse-gas release into the atmosphere. Besides, the use of CO_2 can be helpful for reducing oxygen loss caused by mineral oxidation during gas storage. Furthermore, when CO_2 is used as a cushion gas within the pressure range spanning the critical pressure (5 ~ 12 MPa), larger quantities of compressed air can be injected with less increase in pressure than in the cae of air or an inert cushion gas. So, the risk of overpressure in the reservoir would be lower. However, more studies or experiments are needed to assess the real performance and weigh the economic and environmental costs and benefits of a CAES system using CO_2 as cushion gas. Thermodynamic and sensitivity analyses of the performance of the fossil-fuel–free *trans*-critical energy storage system with CO_2 as working fluids indicate that the energy storage system has good comprehensive thermodynamic performance [110]. A preliminary study with 1D numerical model showed that pervasive pressure gradients bring the position of the air-CO_2 interface close to the well, but undesirable air-CO_2 mixing and subsequent production of CO_2 up the well would happen [84].

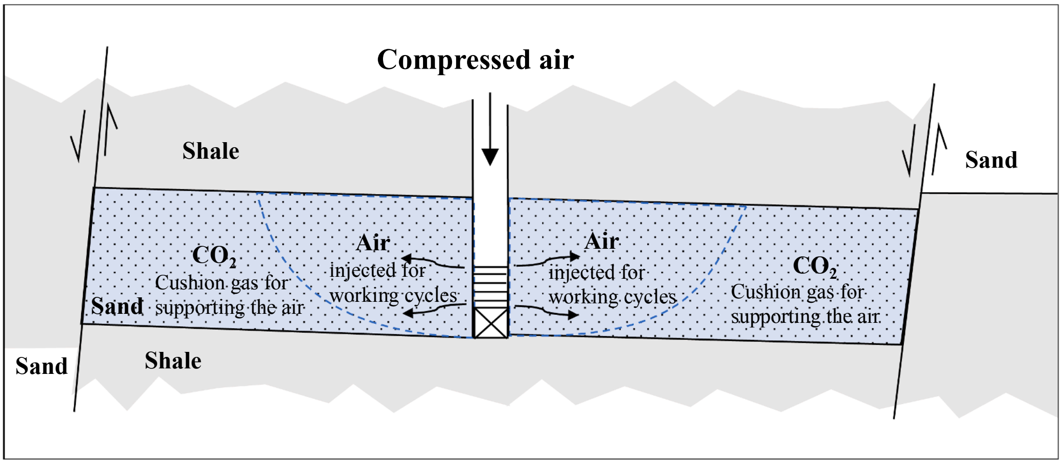

Fig. 14. An idealized single-well compressed air energy storage reservoir using CO_2 as cushion gas (modified after Oldenburg [109]).

3.3.2. Air injection temperature

As for the components of CAES underground, the efficiency improvement ideas focus on the wellbore and reservoir. The Pittsfield test data showed that heat loss was huge around the wellbore [74]. Thermal insulation material for the wellbore is necessary to achieve the anticipated energy storage plan. Similar to geothermal utilization systems, thermal insulation pipes including casing and tubing are an alternative method to prevent heat loss to reservoirs [111]. As for the components of CAES on the ground, the research focus in the future will likely be on the introduction of the CAES system in the grid along with the poly-generation cascaded concept to improve the turnaround efficiency of the CAESA system [7].

Injection temperature and pressure should be within a safety range to make sure that the reservoir can work as designed. For conventional CAES in caverns, the maximum inlet air temperature is limited due to the instability of the salt cavern at temperatures above 52 ℃[112]. Allen et al. [73] suggested that the injection temperature should be up to 200 ℃, and Katz and Lady [56] concluded that an injection temperature of 93 ℃ is desirable for storage at a moderate depth. To prevent reservoir matrix disaggregation and other geochemical effects, the injection temperature should not be over 300 ℃. On the other hand, the injection of dry air at elevated temperature can accelerate dehydration of the storage zone by evaporating and transporting water vapor away from the wellbore [57]. Wiles [59] found that the time required for dehydrating a certain radius from the well decreases with increasing injection temperature and suggested that the maximum allowable injection temperature should be determined by limiting the output temperature from compressors to about 232 ℃.

A preliminary study by Guo et al. [64] with different injection air temperatures (20-200℃) indicated that the efficiency (without considering ground facility) still remain high even if the efficiency would decrease as the temperature increases, as shown in Fig. 15. With lower injection temperature, the considerable advantage of geothermal energy could also be utilized.

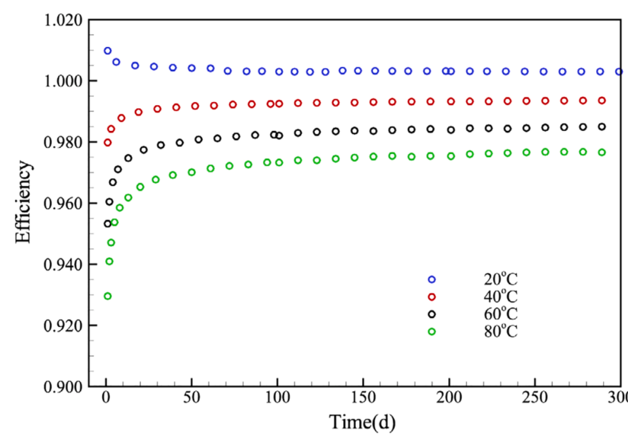

Fig. 15. Energy recovery efficiency comparison of different injection air temperature [64]

3.3.3. Reservoir improvement

Horizontal well and hydraulic fracturing technology have been used to improve the permeability in shale gas production and unconventional hydrocarbon fields [113]. Numerical simulators are key to the design and evaluation of hydraulic fracturing treatments [114]. In Iowa ISEP projects, one long (1900 m) horizontal well was assumed in the simulation model to improve the energy storage scale and efficiency [86]. Guo et al. [83] carried out several hydraulic fracturing scenarios and found that the hydraulic fracturing near the wellbore provide faster pressure support than the horizontal well since the pressure variation occurs mainly in the wellbore nearby. Fig. 16 shows that the pressure variation within 50 m of the hydraulic fracture wellbore meets the minimum and maximum pressure requirements for operating a 135 MW system. While hydraulic fracturing could solve the deliverability problem, there have also been concerns regarding the environmental challenges, such as the induced seismicity [115], groundwater contamination [116], and overuse of freshwater [117].

3.3.4. Bubble boundary fixation

The desirable reservoir property for appreciable efficiency is high permeability in the bubble area and low permeability at the boundary. As for the boundary condition improvement, the slurry injection in petroleum engineering project can be introduced to create a relatively close boundary around the bubble [63,118]. Li et al. [64] investigated the feasibility of man-made low-permeability barriers created by injecting grout with certain properties into high-permeability aquifers. The influence of the critical solidification concentration, time dependency of grout viscosity (i.e., the scale factor of Gel Time Curve), relative density of the grout, and follow-up water injection rate and volume on creating the low permeability barrier was evaluated by carrying out sensitivity analyses [64]. The results indicate that a smaller critical solidification concentration and small-scale factor of Gel Time Curve (a time-dependent function to calculate the viscosity of the pure grout [119]) is favorable for barrier creation, and the optimal relative density of grout depends on the aquifer structure.

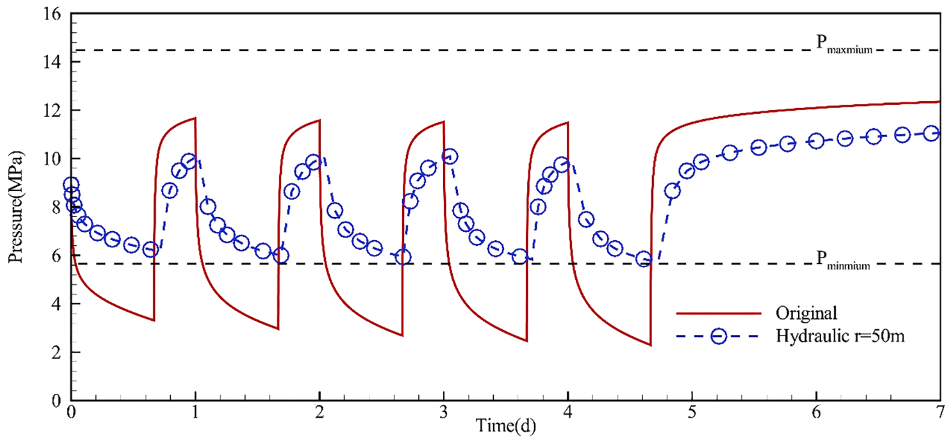

Fig. 16. Pressure variation comparison between long-wellbore and nearby hydraulic fracturing [83]

4. Conclusions

The technology of CAESA is receiving increasing attention due to the growing importance of solar and wind energy and its intrinsic intermittence and fluctuation. Theoretical understanding, analogue comparison, and numerical simulations have been conducted to study the feasibility and suitability of CAESA. Field tests have also been carried out and the results confirmed that aquifers can be the storage reservoir for compressed air energy storage. Previous studies showed that numerical simulation is a reliable tool to assess the feasibility of CAESA for proposed projects. Although the process is similar to natural gas storage in aquifers which has been practiced for several decades, CAESA is still facing challenges. One of the most significant challenges is the geological complexity of aquifers with properties of heterogeneity. The permeability of the storage formation strongly affects the deliverability and the power output of underground CAES storage, and other factors, such as the anticline closure radius, the well configuration, permeability distribution and residual water saturation, influence reservoir performance as well. Laboratory and numerical simulations are required to precisely describe the compressed air behavior in aquifers under conditions of high pressure and temperature. Geophysical prospecting and drilling exploration methods need further development to better understand aquifers' geological and hydrogeological characteristics. These challenges need to be addressed along with efforts in terms of integration with thermal energy storage, chemical reaction prevention, and horizontal well or hydraulic fracturing and man-made boundaries integrated with the existing theoretical and technological developments. Overall, CAESA is a promising technology that can help in accelerating and achieving the transition to renewable energy. However, it still faces several technological and environmental challenges that need to be overcome before it can be widely implemented.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study is supported by the National Natural Science Foundation of China (No.42002255 and No. 41902310), the Chinese Academy of Geological Sciences through Chinese Geological Survey Projects (DD20201165) and Funds (YWF201903, JYYWF20180301), the Lawrence Ho Research and Development fund, the Australian Research Council through Discovery Projects (DP170102886), Jiangsu Natural Science Foundation (BK20180636) and Independent Innovation Project for Double First-level Construction of CUMT (2018ZZCX04).

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